ANALYSIS OF TOPOLOGIES OF ACTIVE FOUR-QUADRANT RECTIFIERS FOR IMPLEMENTING THE INDUSTRY 4.0 PRINCIPLES IN TRAFFIC POWER SUPPLY SYSTEMS

АНАЛИЗ ТОПОЛОГИЙ АКТИВНЫХ ЧЕТЫРЁХКВАДРАНТНЫХ ВЫПРЯМИТЕЛЕЙ ДЛЯ РЕАЛИЗАЦИИ ПРИНЦИПОВ «INDUSTRY 4.0» В СИСТЕМАХ ТЯГОВОГО ЭЛЕКТРОСНАБЖЕНИЯ

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Abstract: *Implementation of the principles of "INDUSTRY 4.0" into the traction power supply systems implies the introduction of power factor correction modes and the possibility of bi-directional energy transfer in the DC traction substations used on railways and subways. The article provides an overview and comparison of active rectifier circuits, which allow to realize power factor correction and eliminate the higher harmonics of the input current. A number of requirements are presented, on the basis of which the optimal scheme for the rectifier of the traction substation was chosen.*
KEYWORDS*: ACTIVE SEMICONDUCTOR CONVERTER, HARMONICS, POWER FACTOR, POWER SUPPLY SYSTEM, ENERGY EFFICIENCY, TRACTION SUBSTATION.*

1. Introduction

On DC traction substations are use diode and thyristor three-phase rectifiers. These schemes have a number of drawbacks. In some cases, they not only do not provide the possibility of energy recovery, have a low power factor, but also a powerful source of higher harmonic components of current in the general network [1, 2]. The presence of higher harmonics of the current has the following negative consequences: distortion of the form of supply voltage; induction in telecommunication and control circles, reduction of the efficiency factor of the power supply system itself and technical devices powered by it. In this regard, the schemes used are morally obsolete. Actual is the search for new circuit solutions for rectifier traction substation installations.

The purpose of this study is to analyze the schemes of active three-phase rectifiers with the correction of the power factor with the forced formation of the sinusoidal input current, as well as the choice of the optimal scheme of the active rectifier for the DC traction substation.

2. Three-phase active full-wave step-up rectifier

There are different topologies of schemes of active rectifiers, which provide correction of the power factor [3, 4]. One of the schemes, which has high energy indices, is the scheme of active full-wave step-up rectifier. This scheme provides a realized power factor close to the one, the mode of continuous currents and the possibility of implementing a bidirectional flow of energy, that is, the possibility of recovery. The scheme of an active step-up rectifier is shown in fig. 1.

The structure of this converter includes six fully controlled keys. Mandatory condition for the realization of the sinusoidal shape of the rectifier input current is the output voltage of the converter should be higher than the phase input of the active rectifier.

The diagram of the input current and the voltage of the active step-up rectifier are shown in fig. 2.

A three-phase active full-wave step-up rectifier is shown in fig. 3, has several distinctive features that make this circuit most convenient for implementation in three-phase active rectifiers:

- the absence of pulsations of the input AC, which leads to a significant reduction of the input EMC filter;

- low level of square root currents in IGBT-keys relative to circuits with three keys and single-circuit circuits of three-phase active rectifiers.

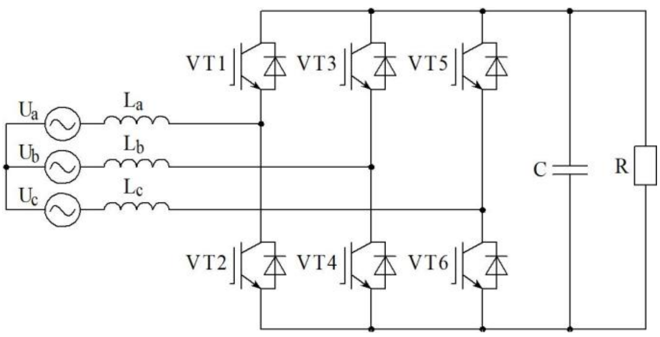

Fig. 1. *Two-level active step-up rectifier with correction of power factor*

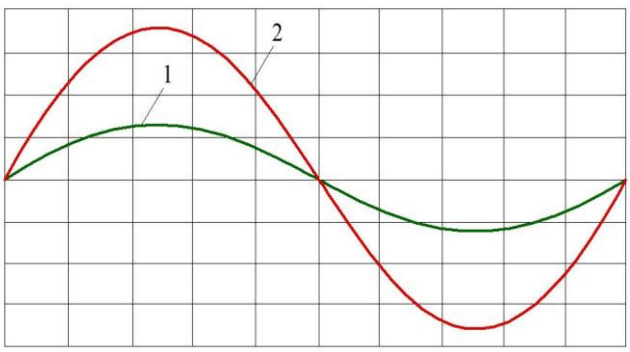

Fig. 2. *The diagram of the input current (1) and the voltage (2) of the active step-up rectifier*

The active step-up rectifier is capable of implementing a bidirectional flow of energy, that is, it provides direct possibility of recuperation [5, 6]. The disadvantage of the scheme is the need to use six active keys to provide a power factor close to the one, when, for example, in the circuit Vienna need only three keys, and in the circuit-breaker, respectively, only one. In addition, due to the fact that the scheme by definition is step-up , there is no possibility of adjusting the output voltage in the range from zero to the value of the amplitude of the phase voltage, that is, the given circuit design can not replace the traditional thyristor downregulation of the active rectifier with the control at the angle of unlocking.

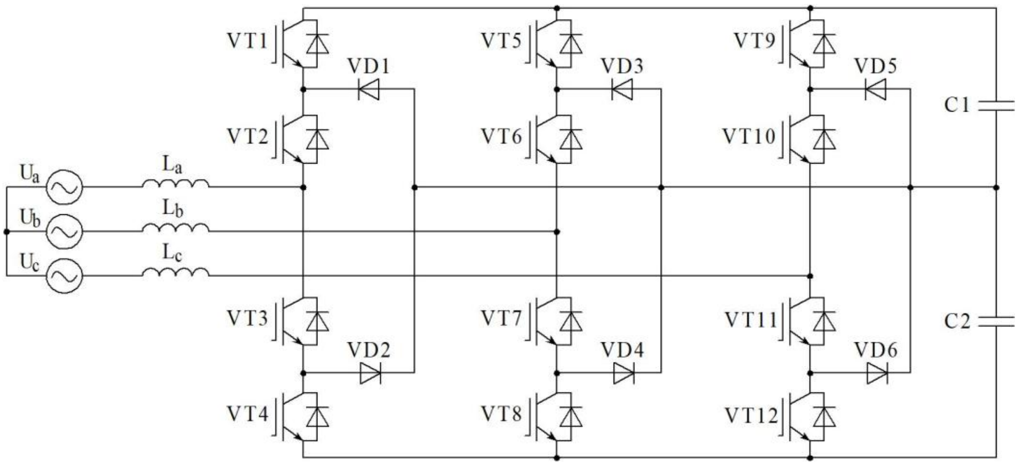

Fig. 3. *Three-level active step-up rectifier with correction of power factor*

3. Active full-wave step-down rectifier

A three-phase active rectifier is shown in fig. 4, has the ability to adjust the output voltage in the range from zero to the nominal value of the network, while providing a sinusoidal input current and a power factor close to one [7, 8]. However, the circuit of the active step-up rectifier is more convenient and has great advantages.

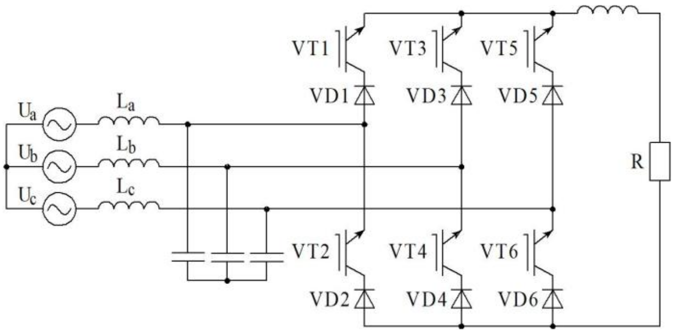

Fig. 4. *The active full-wave step-down rectifier*

Unlike single-phase execution, a three-phase step-down schema can transmit power to DC load with minor distortions of input currents, ie the shape of the input currents is almost sinusoidal. When the instantaneous value of one phase voltage is zero, the other two phases are non-zero and transmit power to the load. This converter has an adjustable value of the output voltage in the range from zero to the value of the amplitude of the phase voltage of the network [9]. This type of converter has similarities to a well-known autonomous current inverter, except that the circuit operates in rectifier mode with the control of high-frequency PWM and provides a power factor close to one.

For the correct operation of the converter, two-quadrant bipolar keys are required, which are well implemented by the serial connection of the IGBT of the transistor and the power diode. The disadvantage of this scheme is the higher specific losses in the valves compared with the valve rectifier, due to higher mean-square values of currents in the serial connection of the IGBT and the diode [10, 11]. The converter is capable of operating inverter mode, that is, it provides the possibility of recuperation. However, recuperation in this type of converter is possible only with the negative polarity of the output voltage, which makes it impossible to use it at the traction substation without additional polarization power devices. Also, in order to provide a sinusoidal input current, an expensive dimensional input filter is usually needed to smooth the input currents pulsations.

The scheme of the Vienna rectifier is shown in fig. 5, is also a kind of circuit of active rectifiers with correction of the power factor.

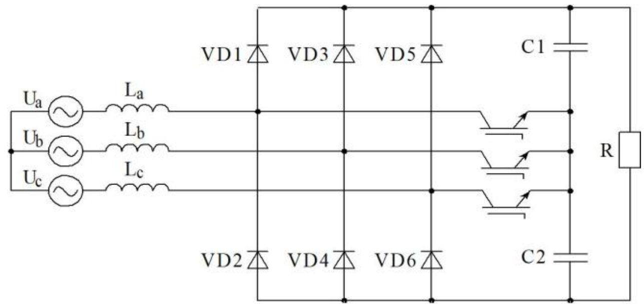

Fig. 5. *The scheme of the Vienna rectifier*

4. Single-key three-phase active rectifier

Three-phase active rectifiers described in the previous sections, in their topology contain six keys, which, in comparison with passive (diode) rectifiers, makes the circuit of the active converter more expensive. In view of this, the question arises – which minimum number of active keys is necessary for the implementation of an active rectifier with correction of the power factor. Can implement power correction using a simple diode circuit using passive filters. Proceeding from this, for the realization of a three-phase rectifier only diodes are required. However, when you need to control (adjust) the output voltage, you need at least one high-power controlled key. In addition, if need to significantly reduce the input filters and implement active power correction, just one active key can be applied in the same way. However, this scheme will not enable the implementation of a bidirectional flow of energy (recuperation) [12].

Consequently, theoretically, only one active key is necessary for the implementation of the formation of the input current (correction of the power factor) with the implementation of regulation of the level of output voltage, but without the possibility of implementing a bidirectional flow of energy. Several circuit-switched circuits of three-phase rectifiers were presented earlier. However, it should be noted that these schemes require the use of additional reactive filters.

Single-key scheme of a three-phase active step-up rectifier, implemented on the principle of an enhancer, is shown in fig. 6.

The transistor Q1 is governed in the same way as in an DC-DC step-up converter. The input current $i_a(t)$ is shown in fig. 7.

The inductances L_a, L_b and L_c operate in intermittent currents in conjunction with the diodes D1÷D6. At the end of the increase in the current in the throttle, the current reaches its peak value, which is also proportional to the applied voltage of the three-phase network. When the transistor Q1 is closed, then the diode D7 becomes straightforward and the throttle transfers the accumulated energy into the load. Since the peak of the input currents is proportional to the amplitude of the linear voltage, the average value of the input currents is also approximately proportional to the value of the linear voltage of the network. In this way, the effect of the presence of a three-phase input resistance is achieved. The three-phase single-circuit charging rectifier has a sufficient number of higher harmonics, but their number and the overall harmonic distortion factor can be reduced with increasing output voltage.

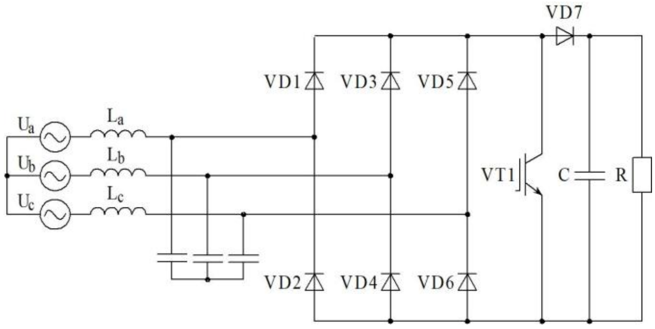

Fig. 6. *Single-key scheme of a three-phase active step-up rectifier*

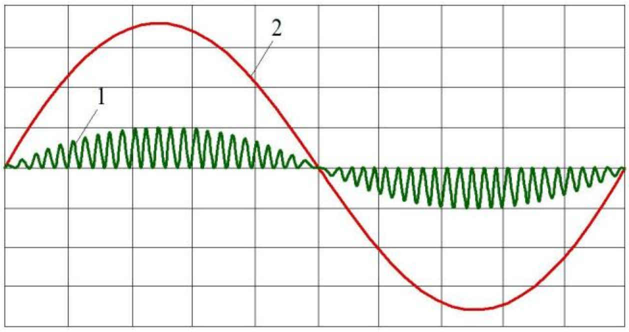

Fig. 7. *The input current (1) and the voltage (2) of the single-key step-up converter*

The three-phase single-key step-up converter has a clear advantage in the simplicity of its control system. The transistor can operate at a constant switching frequency.

The change in the PWM fill factor allows you to adjust the value of the output voltage. Sufficiently is one active semiconductor such as MOSFET or IGBT for implementing this converter. A disadvantage is the need to use an input filter to reduce the incoming current pulsations.

5. Comparative analysis of power correction schemes

In comparison, an analysis of the modernization of the three-phase active rectifier with control on the opening angle is given. In this case, it is necessary to control the value of the output voltage, in the range from zero to the value of phase voltage of the network. In this case, any of the schemes may be applied. In this case, the simplest is the circuit of an active controlled step-down rectifier, is shown in fig. 4. Schematics with one active key, are shown in fig. 5, 6, can also be used. In this case, will make a comparison of the downline single-circuit active rectifier with a full-circuit diagram.

Comparison of the peak values of the key load voltage and current for a 25 kV rectifier unit is shown in table 1. The value of the input voltage of the rectifier unit is 440 V, the value of the output voltage is 370 V at a current of 67,5 A. Also it shows the value of the total power load of the converter keys (the sum of the power of all keys is taken).

The implementation of a single-switch converter is usually considered only for small capacities due to the increased peak value of the voltage of the key, which leads to increased losses in the switches themselves. However, these causes are not related to the AC-DC performance of the active rectifier due to the fact that the increased value of peak current at resonant switching is offset by the lower value of the specific load of circuit keys, which leads to the possibility of more efficient energy dissipation. The use of full-circuit schemes leads to a low specific load of the key, which in different implementations can be both an advantage and a disadvantage of this scheme. However, if compare the full-circuit with six keys and compare it with a rectifier unit, which is six parallel-connected circuit-switched circuits, then the peak value of the current in each key of such an assembly will be 30 % lower compared to the six-key scheme.

Table 1

Comparison of single-key rectifier scheme with active full-wave scheme

Parameter	The full-wave step-up scheme an active rectifier	The full-wave step-down scheme an active rectifier	The scheme of the Vienna rectifier	Single-key scheme an active rectifier
Output voltage	Above the amplitude of the network voltage	Below the amplitude of the network voltage	Above the amplitude of the network voltage	Above the amplitude of the network voltage
Voltage on the keys	U_{out}	U_{out}	$U_{out}/2$	U_{out}
Recuperation capability	Yes	When changing the polarity of the output voltage	No	No
Number of fully control keys	6	6	3	1
Number of diodes	6	6	6	7
Input current of active rectifier	Continuous sinusoidal	Continuous sinusoidal	Continuous sinusoidal	Intermittent, impulsive
Realized power factor	0,98÷0,99	0,98÷0,99	0,98÷0,99	0,92
Cos φ	0,99÷1	0,99÷1	0,99÷1	0,99÷1
Coefficient of harmonic distortion of current form THD, %	5÷12	5÷12	5÷12	60÷90

6. Imitation simulation

An appropriate simulation model was developed for a more detailed study of electricity quality indicators in the full-wave step-up rectifier in the MATLAB software, is shown in fig. 8. The results of the simulation of the work of the active rectifier during the transition from the regimen to the recovery mode are shown in fig. 9. As can be seen from fig. 9, both in the mode of straightening, and in the recuperation mode, the shape of the consumed current is sinusoidal. In this case, the transition from regimen to recuperation mode is a fairly qualitative transition process.

Results of the Fourier analysis of the phase current of the active rectifier are shown in fig. 10. As can be seen from fig. 10, the shape of the input current contains only 2,13 % of the higher harmonics that meets the requirements of international standards for the quality of electric energy.

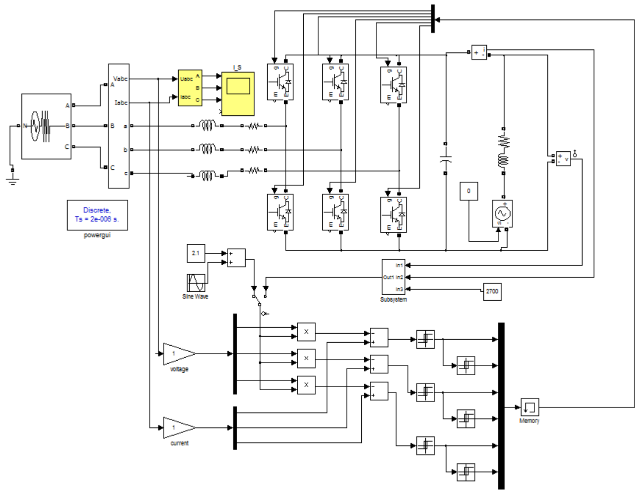

Fig. 8. *Imitation model of an active rectifier*

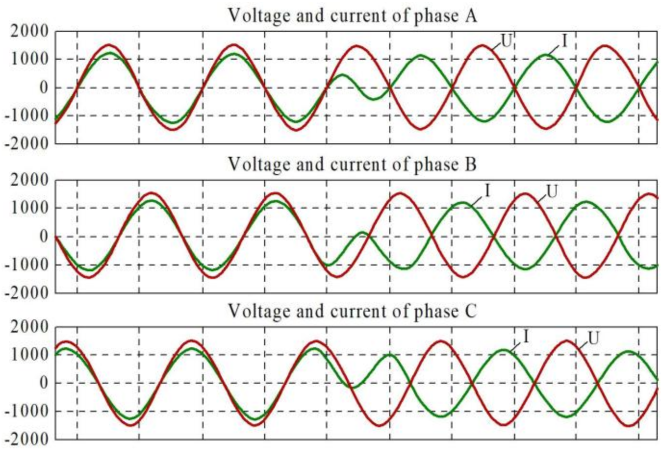

Fig. 9. *Results of imitation simulation*

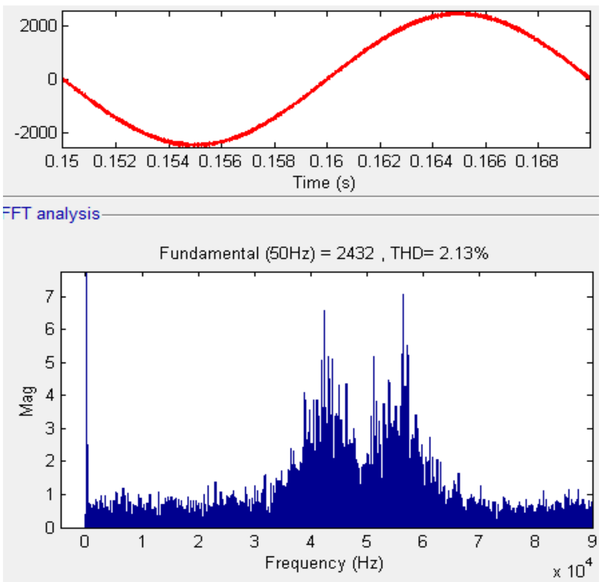

Fig. 10. *Fourier analysis of the phase current of the active rectifier*

7. Results and discussion

Single-key schemes of active rectifiers can be actively used in schemes of small and, in some applications, average power. However, with the implementation of a powerful rectifier unit with a power of several megawatts, the execution of a single-key scheme is inadmissible from the reasoning of the reliability of the converter at high values of pulsed currents, as well as the presence of high content of higher harmonics of current that appear due to the mode of intermittent currents.

At the same time, it is necessary to realize the mode of energy recuperation from the contact network to the general industrial network. In connection with this, it was concluded that the most expedient scheme for modernizing the traction substation of a direct current is an active rectifier based on a full-wave step-up scheme.

8. Conclusion

The paper presents an overview of modern schemes of active three-phase rectifiers with correction of power factor. An analysis of existing circuits was performed and a choice of optimal scheme for a DC traction substation was made.

The optimal scheme for a traction substation of a direct current is the scheme of an active three-phase full-wave step-up rectifier. In the future it is necessary to study the control systems of the active rectifier, as well as the work of the most active rectifier during a dynamic load change.

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